DIY Absolute Tele-Colorimeter using a Camera-Projector System

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(a) (b) (c) (d)

Figure 1: (a) Absolute XYZ values captured by a professional 2D color analyzer. In (b), our estimates. In (c)-(d) application of our technique for radiometric compensation. (c) Uncompensated image projected on a textured surface. (d) Compensated image, projected on the same surface. The estimation of the surface gamut partly relies on a camera characterized with our method.

ABSTRACT

Image-based reflectance measurement setups lower costs and increase the speed of reflectance acquisition. Unfortunately, consumer camera sensors are designed to produce aesthetically pleasing images, rather than faithfully capture the colors of a scene. We present a novel approach for colorimetric camera characterization, which exploits a commonly available projector as controllable light source, and accurately relates the camera sensor response to the known reflected radiance. The characterized camera can be effectively used as a 2D tele-colorimeter, suitable for image-based reflectance measurements, spectral prefiltering and spectral up-sampling for rendering, and to improve color accuracy in HDR imaging. We demonstrate our method in the context of radiometric compensation. Coupled with a gamut-mapping technique, it allows to seamlessly project images on almost any surface, including non-flat, colored or even textured ones.

CCS CONCEPTS

• **Computing methodologies → Reflectance modeling**; **Computational photography**; *Image-based rendering*;

KEYWORDS

DSLR camera, Colorimeter, Tristimulus Values, HDR, Reflectance

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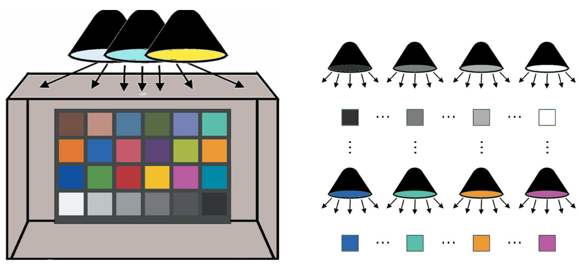
1 INTRODUCTION

Radiometric functions such as BRDF, SVBRDF and BTF are commonly used to describe the appearance of real world materials and achieve photo-realism. Accurately measuring the reflectance properties of a material can be expensive and time consuming.

In the last 20 years a number of image-based measurement setups have been developed [Guarnera et al. 2016]. They trade accuracy for increased versatility, higher throughput and lower costs, by taking a series of photographs of a surface and requiring mainly off-the-shelf components. However, the typical design of consumer camera sensors focuses on good contrast and vivid colors, largely disregarding the colorimetric accuracy of the acquired scene.

In order to use a DSLR for color and reflectance measurements, acquired RGB values must be converted into meaningful radiometric and colorimetric data. Color characterization techniques aim to establish a relationship among the sensor responses to a set of colors and the corresponding colorimetric values (CIE XYZ). To derive such a relationship, many techniques make use of a reflective Color Target (CT) with a limited number of color patches (*e.g.* 24 on a GretagMacbeth ColorChecker®), illuminated by a small set of illuminants (3~7 on most light booths) (Fig. 2 (a)). The sparse sampling of the incident lighting spectra and surface reflectance leads to inaccurate results and limits them to low dynamic range imaging, since only the relative spectral power distribution is preserved. In practice, these approaches can be used only in similar illumination conditions to those selected for characterization.

In our work, we abandon the physical CT and light booth paradigm and make use of a projector, used as a controllable light source. By modulating the relative and absolute spectral distribution of the light beam, a high number of illuminants can be used to characterize a camera (Fig. 2 (b)), which projected on arbitrary targets lead to a vast set of color patches to use for characterization. The freedom in designing the illuminants allows us to reduce the sampling in the spectral reflectance space, even to a single spectrally neutral target, while removing any bias when the characterized camera is to be



(a) (b)

Figure 2: (a) Standard color target / light booth setup. (b) The proposed projector setup.

used in new lighting conditions. Furthermore, by preserving the absolute scale of the illuminant, our technique provides accurate XYZ estimates on a physical scale (cd/m^2), even from a single shot.

Previous Work. Only a few techniques aim to estimate absolute XYZ values. [Martínez-Verdú et al. 2003] measured the sensor's characteristics with a monochromator, a single wavelength λ at a time, over the visible spectrum. Their setup includes a standard light booth and color checker; the ground truth is measured with a spectro-radiometer. [Kim and Kautz 2008] proposed an ad-hoc transparent target, suitable for HDR imaging. The XYZ values are computed directly from the RGB values acquired with a HDR sequence, using a 3x3 matrix derived through linear least-squares, which embeds many factors.

2 PROPOSED TECHNIQUE

An A4 white uncoated professional photo paper, without bleaching (roughly lambertian and spectrally neutral), is used as target. We limit the characterization set to the 24 illuminants which reflected by the target produce the XYZ values of a physical ColorChecker® , and demonstrate that they suffice to outperform prior art. The ground truth can be measured by a 2D tele-colorimeter; alternatively, a 1D colorimeter could be used, by sampling the target.

For each reflected tristimulus value a HDR sequence is acquired; the raw RGB values are normalized by our pipeline, accounting for noise floor n, saturation level S, areas beneath the sensor spectral sensitivity curves, lens fall-off. We compute the XYZ values as:

$$[X, Y, Z]^T cd/m^2 = \mathcal{M} \cdot \mathcal{T}([L(R), L(G), L(B)])^T \ cd/m^2 \quad (1)$$

where $\mathcal{M}$ is the colorimetric characterization matrix, $\mathcal{T}$ is a polynomial transformation, and $L(R)$, $L(G)$, $L(B)$ are the luminance estimates obtained individually from each channel of the camera.

Given the set of neutral tristimulus values $X_i = Y_i = Z_i$, $i = 1, \ldots, \#_{stimuli}$ and the corresponding HDR photographs (Fig. 2b, bottom row), for each pixel p_i in the sensor lattice we have:

$$[R|G|B]_{p_{i,t}} \propto \left[\mathcal{F}_{R|G|B}(T, Y_i, C_{R|G|B}, t)\right]_p + n \quad (2)$$

since $Y = \sum_{\lambda \in \omega} I(\lambda) S(\lambda) \triangle\lambda$, under the hypothesis $X = Y = Z$, where ω is the visible spectrum of the light, $\mathcal{F}_{R|G|B}$ are the per-channel sensor responses to the luminance, T is the lens transmittance, and $C_{R|G|B}$ are the sensor spectral sensitivity curves t is the exposure time. To model the sensor response to the luminance Y, the normalized values $[R', G', B']_{i,t,N}$ are fitted to the corresponding known luminance values Y_i, $i = 1, \ldots, \#_{stimuli}$, for a given pair $\{t, N\}$. From Eq. 2, their inverse are readily derived:

$$\mathcal{F}^{-1}_{R|G|B}\left(R'|G'|B', t, N\right) = L(R|G|B) = Y \ cd/m^2 \quad (3)$$

The matrix $\mathcal{M}$ is found by means of non-linear optimization [Bianco et al. 2007], using the data derived from all the color patches:

$$\mathcal{M} = \arg\left(\min_{M \in \mathbb{R}^{3 \times P}} median(E) + mean(E) + max(E)\right) \quad (4)$$

$$E = \left\|[X, Y, Z]^T - M \cdot \mathcal{T}([L(R), L(G), L(B)])^T\right\|_1 \quad (5)$$

where $||\cdot||_1$ is the L_1 norm, $\mathcal{T}$ is the same as in Eq. 1, and P is the number of polynomial terms given in output by $\mathcal{T}$. For a complete description of the proposed method see [Guarnera et al. 2018].

3 RESULTS AND CONCLUSION

We compared the estimates from a characterized, inexpensive Canon 40D camera with the measurements of a costly professional 2D Color Analyzer, for a set of scenes with complex geometry, spatially varying reflectance and light sources with different spectral power distributions (see Fig. 1 (a)-(b)). The measured colorimetric error ΔE_{00} in most cases is below a perceptible difference, thus making our technique suitable in a wide range of applications. For instance, it can be used in the field of radiometric compensation, to project images on any kind of surface, even not specifically intended to be used as screen (*e.g.* non-flat, colored or even textured). In this context, there is a need of maintaining accurate color rendition, irrespective of the characteristics of the surface used to display images. This can be achieved with a projector-camera system, making a per-pixel acquisition of the projection surface and estimating its gamut [Naccari et al. 2016]. Using this information a compensation image is derived, in order to correct for geometric distortion and to neutralize the color cast due to the underlying surface and texture (see Fig. 1 (c)-(d)); as a drawback, the projected image might show reduced contrast, brightness and color saturation with respect to the same image projected on a white canvas. Clearly, the more accurate is the model of the projection surface acquired by the camera, the more the projected result appears seamless. The proposed method allows a very accurate acquisition of the projection surface, thus reducing the perceived visual artifacts in projected images, while permitting an optimal preservation of the luminance, contrast and color saturation of the displayed content.

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